Single Ion Mass Spectrometry and the Fine Structure Constant

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Using a Penning trap single ion mass spectrometer, we have measured the atomic masses of 13 isotopes several of which are important for fundamental metrology and fundamental constants. The accuracy of the measurements, typically 10^{-10}, represents one to three orders of magnitude improvement over previously accepted values. A wide variety of self consistency checks greatly reduces the possibility of unknown systematic errors.

This new level of accuracy is reached by measuring the cyclotron frequency (which is inversely proportional to the mass) of a single molecular or atomic ion trapped in a highly uniform magnetic field. Trapping the ion allows the long observation time necessary for high precision. Using a single ion is crucial for high accuracy since this avoids the complex frequency perturbations caused by multiple ions. We have developed ultrasensitive superconducting electronics to detect the miniscule currents ($\approx 10^{-14}$ amperes) that the ion's axial motion induces in the trap electrodes. The cyclotron motion is detected phase coherently via an RF coupling to the axial motion. In the spirit of the separated oscillatory field technique, RF drives and couplings are applied only briefly at the beginning and end of a measurement thus vastly reducing systematics and uncertainties involved with continuously observing the cyclotron motion. A typical measurement time of only 1 minute yields a precision of $\approx 2 \times 10^{-10}$ with the current limitation being short term fluctuations of the magnetic field.

Our current level of precision has allowed us to perform several important experiments in physics and metrology. Recently we measured the masses of several alkali atoms as part of a program to determine the fine structure constant α from measurements of atomic photon recoil frequency shifts[1]. This technique is based on simple physics and hopes to ultimately achieve the several ppb accuracy needed to test the QED determination of α extracted from measurements of the electron g factor.

Earlier, we made a precise recalibration of the γ-ray spectrum. This was done by comparing the masses of ^{14}N + n and ^{15}N. By converting the measured mass difference Δm to an energy difference using Einstein's well known formula $E = \Delta mc^2$, the energy of the γ-rays emitted in the neutron capture process connecting the isotopes was determined to 1 electron volt. This uncertainty is 80 times smaller than the discrepancy with the previous calibration of these γ-rays which are widely used as a wavelength standard in the 2 to 10 MeV range.

Our 10^{-10} capability in the comparison of atomic masses exceeds the known drifts of secondary standard kilogram masses used to transfer the international kilogram to the various national standards laboratories. This suggests that a program to replace the "artifact" kilo-

Table 1: Measured Atomic Masses.

Species	MIT Masses (amu)	1993 Masses (amu)
^{1}H	1.007 825 031 6 (5)	1.007 825 035 0 (120)
n	1.008 664 923 5 (23)	1.008 664 919 0 (140)
^{2}H	2.014 101 777 9 (5)	2.014 101 779 0 (240)
^{13}C	13.003 354 838 1 (10)	13.003 354 826 0 (170)
^{14}N	14.003 074 004 0 (12)	14.003 074 002 0 (260)
^{15}N	15.000 108 897 7 (11)	15.000 108 970 0 (400)
^{16}O	15.994 914 619 5 (21)	15.994 914 630 0 (500)
^{20}Ne	19.992 440 175 4 (23)	19.992 435 600 0 (22000)
^{23}Na	22.989 769 280 7 (28)	22.989 769 660 0 (2600)
^{28}Si	27.976 926 532 4 (20)	27.976 927 100 0 (7000)
^{40}Ar	39.962 383 122 0 (33)	39.962 383 700 0 (14000)
^{85}Rb	84.911 789 732 (13)	84.911 792 400 (2700)
^{87}Rb	86.909 180 520 (15)	86.909 185 800 (2800)
^{133}Cs	132.905 451 929 (27)	132.905 447 000 (3000)

gram mass standard by a definition involving an atomic standard of mass should be undertaken. Towards this end we have accurately determined the atomic mass of ^{28}Si since ultrapure silicon crystals have been suggested as a means to realize this new definition.

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[1] M. P. Bradley, J . V. Porto, S. Rainville, J. K. Thompson and D. E. Pritchard, *Phys. Rev. Lett.* **83** 4510 (1999).